25 Virtual Reality Tools for Testing Control Room Concepts

ASGEIR DROIVOLDSMO AND MICHAEL LOUKA

PARTIAL LIST OF SUPPLIERS

Autodesk (http://usa.autodesk.com/)
Barco (http://www.barco.com/)
Bentley Systems (http://www.bentley.com/en-US/)
Blender Foundation (http://www.blender.org/)
Dassault Systèmes (http://www.3ds.com/)
EON Reality (http://www.eonreality.com/)
Mechdyne (http://www.mechdyne.com/)
Parametric Technology Corporation (http://www.ptc.com/)
Okino Computer Graphics (http://www.okino.com/)
RealD (http://www.reald.com/)
Eos Systems (http://www.eossystems.com/)
Right Hemisphere (http://www.righthemisphere.com/)
Siemens PLM (http://www.siemens.com/entry/cc/en/)

Cost: Laptop and desktop-based computer systems with adequate 3D graphics acceleration range from \$1.5 to \$5K. Projection-based computer systems range from \$5K to over \$1M, depending on the display technology and resolution. In addition, there is the cost of software, which typically ranges from \$500 to \$50K, largely depending on its capabilities for creating detailed models efficiently and for supporting effective and accurate model testing, and on the level of technical support offered by the supplier.

INTRODUCTION

Recognized review models for the design process of control rooms [1–3] have a similar general approach to the handling of output from the human-system interface (HSI) design verification and validation (V&V). They recommend an iterative process where deviating verification results should be used as input to the next iteration or phase in the design process. The problem with this approach is that there is a shortage of tools supporting HSI V&V in the early phases of control center design.

Virtual reality (VR) technology has proven to be a promising, powerful, and cost-effective tool in control room design works [4,5]. It enables designers to spend more time evaluating creative new ideas, helping them to identify and eliminate potential problems early in the design process, and lowers the threshold for end users and human factors specialists to participate more actively in the early design process.

This chapter describes a human-centered design process for a control room and the practical use of VR technology as a tool for testing control room concepts.

VIRTUAL REALITY

VR technology enables users to immerse themselves in an artificial environment simulated by a computer, with the ability to navigate though the environment and interact with objects in it. The term “virtual reality” is often used interchangeably with *interactive 3D*, *real-time 3D*, *virtual environments*, *synthetic environments*, *visual simulation*, and other similar terms describing real-time, interactive, 3D graphical simulation.

Two keywords in the field of VR are *presence* and *immersion*. VR systems seek to immerse the user in a simulation so that the user has a sense of being present in a virtual environment. The degree of immersion depends primarily on the computer hardware used whereas presence is achieved if the virtual environment causes the user to suspend disbelief and accept the computer-generated experience as real.

A computer system that generates an artificial world that tricks the user into feeling part of it would not be a complete definition of VR because it lacks the vital component of interactivity. VR is a three-dimensional (3D) user interface in which the user can perform actions and experience their consequences. It is a multidimensional, real-time simulation rather than a linear animation with predefined camera movement. This is what distinguishes VR from recorded, computer-generated, images used in movies and on television and from real-time computer animation where the user is a passive viewer. Unlike pre-rendered images of a 3D environment, the user of a VR system can usually move around freely in a virtual environment.

In the context of control room design and testing, VR technology enables a designer to interactively construct a virtual control room, view the room from the inside as if it were a physical environment, and simulate moving around in the room, checking lines of sight, distances for legibility of labels, clearance, access, etc. This flexibility is highly suited to human-centered iterative design processes.

VR SOFTWARE REQUIREMENTS FOR DESIGN AND TESTING

In order to evaluate whether an off-the-shelf VR software package can be used effectively for control room design and testing, it is important to investigate what facilities the software provides. Software packages designed for product or architectural design typically provide most, if not all, of the features that are desirable. In some cases, additional features required can be implemented by a programmer or be supported by an additional specialized piece of software (e.g., for virtual humans and ergonomics), but often a little ingenuity in the design of special 3D objects that can be added to a model and be moved around at will is all that is required. Examples of such special objects are semi-transparent view cones, semi-transparent spheres for viewing ideal distances, virtual rulers for checking distances, and virtual protractors for measuring angles.

The key features required of a VR software package for control room design and testing are that the user can interactively add 3D objects to a virtual layout, can move things around in the layout, can move the view to any position, and can measure distances accurately. How accurately and efficiently this can be done depends on the capabilities of the software.

Other useful features include the ability

- For objects to snap to an invisible user-defined grid when positioned in a virtual control room layout
- To group objects together so that they can be treated as a single aggregate object, to make moving them around and duplicating them easier
- To link objects to each other, for example, link a computer display to a desk so that the computer display can be moved independently of the desk but moves with the desk if the desk is moved
- To constrain objects so that they can only be moved in a predefined manner (e.g., rotated around a specific axis or moved in a specific plane) or can be locked in place to prevent accidental repositioning

The manner in which a user interacts with the 3D model depends on the selected VR hardware and software. In most cases, a desktop computer with 3D graphics acceleration and a VR software package are all that is necessary. This basic form of VR is often called desktop or fishtank VR (as it is more like looking into a fishtank then being a fish in the fishtank). The user utilizes a two-dimensional (2D) pointing device, such as a mouse or touchpad, to navigate, select, and manipulate objects, and generally control the software system. It is becoming increasingly common to combine a 2D pointing device with a 3D input device, using one of the devices for navigation and the other for interacting with the system and virtual objects.

Desktop VR is an effective and inexpensive option that can be easily deployed. Some 3D graphics cards support stereoscopic output, enabling users to view a model with an enhanced sense of depth. The desktop 3D experience can thus be enhanced by introducing a stereoscopic display. Furthermore, a stereoscopic-capable projector and a large screen can enable several people to work together in a meeting room, with one user controlling the computer. Of course, the use of a projector to facilitate teamwork in the design process is also useful with a conventional projector, but a large stereoscopic display gives the user a greater sense of seeing a real room when viewing the virtual prototype, especially if the view is configured to resemble a full-scale view. Stereoscopic displays, projected or otherwise, typically require that users wear special glasses. While most users find that stereoscopic viewing enhances their spatial understanding and experience little discomfort, some experience nausea and headaches, either due to the refresh rate or motion sickness, which appears to be more easily induced when viewing stereoscopic images, so it is generally advisable to take regular breaks.

For a greater sense of immersion, head-mounted displays or multi-screen projection systems can be used to place the user inside the model to an even greater extent than a single large screen. While the hardware required to do this comfortably, with motion tracking and 3D input devices, is relatively costly, immersive VR can be useful for walkthroughs of a virtual environments, to experience the environment from the perspective of the end user in as realistic a manner as possible. The purchase of a high-end immersive VR system purely for control room design and testing may be difficult to justify from a cost-effectiveness point of view, if it will only be used for one project; however, many large organizations have such facilities that can be accessed and utilized for limited periods, and some universities and visualization centers have such facilities that can be hired. Head-mounted displays have limited field of view and display resolution, and can only be used by one person at a time, so for design walkthroughs, projection-based systems are generally more useful.

The VR software package used may provide multiuser networking features that enable geographically spread users to view and manipulate a shared 3D model simultaneously. This feature is potentially useful in situations where it is inconvenient for a design team to meet physically. A simpler form of distributed collaboration can be achieved by distributing a copy of the 3D model files by e-mail or from a website to project participants for comment. The master copy can then be updated based on feedback received. In either case, the distributed users will usually need to install software that can be used to view the 3D model. The software may include features for adding annotations to the model, which can improve communication by reducing the risk of ambiguous feedback.

CREATING 3D OBJECTS

Model rooms and objects to position in them can be constructed using a 3D modeling package, a 3D scanning system, or a combination of both. For a control room design project, a library of rooms and objects should be prepared for use with the VR software. Some 3D design software is supplied with libraries of pre-built 3D objects, and many vendors, in particular those that sell furniture, can provide 3D models of their products, so the number of new 3D objects that need to be created may be limited. As 3D modeling can be time-consuming, reuse of existing 3D objects is cost-effective and time saving.

Typically, a 3D computer-aided design (CAD) package is used to model 3D objects. Most CAD packages are capable of exporting 3D object data in a format understood by VR software systems. Open formats for 3D models intended for interactive use include ISO VRML97 [6], ISO X3D [7], and COLLADA [8]. However, there are fundamental differences between 3D CAD models and 3D models intended for interactive use, which usually need to be taken into account when preparing objects created in a CAD package for use in a VR system. In particular, CAD models emphasize the physical properties of solid objects, whereas VR models emphasis the visual appearance of surfaces. When models are exported from a CAD system, curved surfaces are usually converted into polygons that approximate the original curve. Often the number of polygons generated is too large to be used efficiently as a VR model, but optimization software is available, which can be used to reduce the number of polygons without significantly degrading the appearance of the object. In some cases, such optimization is built into the export routines of the CAD software or the import routines of the VR system.

While CAD systems can be used to create accurate models, most systems do not support techniques for modeling surfaces that are used by VR systems to significantly enhance the visual appearance of objects. In particular, most CAD systems have limited, if any, support for applying images (textures) to the surfaces of objects in order to “fake” detail. However, textures can be applied to objects created in CAD systems by importing the geometry into a 3D modeling package that supports textures and then exporting the 3D data in a format supported by the VR system.

Unless CAD models of buildings and objects already exist, which can be used to produce 3D objects for use by the VR system, it is usually more efficient to use a 3D modeling package dedicated to the creation of models for real-time 3D graphics or animation. Such packages typically provide support for modeling at a polygon level, enabling the creation of highly efficient and attractive 3D objects. It is especially important that objects are optimal in cases where conventional instruments are modeled in large numbers since the total number of polygons that a computer needs to render can quickly become inefficiently large, significantly affecting the usability of the system due to performance considerations.

3D scanning systems can be used to digitize existing objects or environments. The scanning process usually consists of a *sensing* phase and a *reconstruction* phase. In the sensing phase, raw data are captured, and in the reconstruction phase the collected data are processed to convert it into a 3D model. The processing in the reconstruction phase may be fully automated, but more often requires some human effort. Common digitization techniques include tracking, laser scanning, and photogrammetry.

Digitization techniques based on tracking work by positioning a probe on a physical object surface and telling a computer to record the probe’s position in space. After a sufficient number of positions have been sampled, reconstruction software can be used to convert the points into a mesh representing the object. This technique would not be appropriate for digitizing a whole room with a large number of flexible pipes, but can be used to scan individual objects, and can work well in combination with photogrammetry techniques.

A more efficient technique than using a probe is to use a laser. Laser scanners are typically positioned in a room where they rapidly sample the distance between the laser device itself and the surfaces of objects in the room to create a point cloud, which is then processed to create a 3D model. In order to scan an entire room effectively, it is usually necessary to take samples with the scanning device placed in a number of different locations in the room. Although some of the processing of the data can be done using software, the result is typically a large mesh that may need human intervention, using 3D modeling software, to break up into smaller, distinct, geometric objects.

Photogrammetry techniques can be used to process one or more photographs to create a photorealistic 3D model. There are a number of different approaches to this, some of which are automated while others require human intervention.

Photogrammetry and laser scanning techniques can be used both to scan individual objects and entire environments. Furthermore, these techniques can be combined effectively, using both a laser and a camera on a tripod to acquire data.

In general, the most efficient manner in which to construct a 3D model of a control room for design purposes is for a human to create models using a 3D CAD or 3D modeling package, using photographs taken with a camera on a tripod to aid in the production of textures.

Using VR in the Control Room Design Process

VR should be viewed as a support tool during the design work, that is, during the preliminary and detailed design, when we consider development of a control room and/or control room upgrading. To ensure usability, human factors and operational experience input must be included at an early stage in the system design. A design process can be described in many different ways, but the description in Figure 25.1 is believed to cover what selected standards and guidelines [1,3,9–16] recommend for control rooms. For continuity in the development and best result, the use of a VR model should start as early in the design process as possible. Development should be an integrated part of all analysis and design phases described below.

Projects differ in their nature, and based on the job that has to be performed, the design team needs to be put together to fulfill the needs of the project. The design team will often

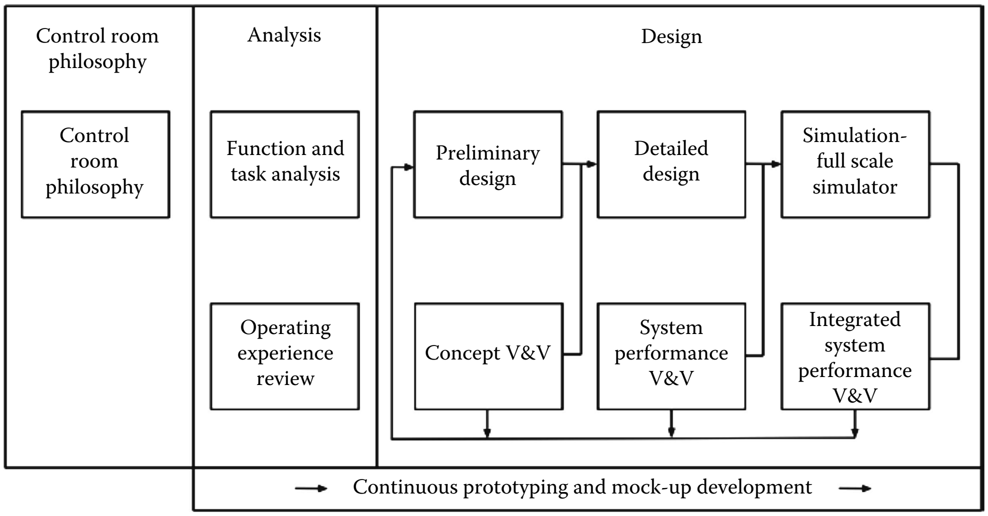
Control room philosophy
Analysis
Design
Control room philosophy
Function and task analysis
Operating experience review
Preliminary design
Detailed design
Simulation-full scale simulator
Concept V&V
System performance V&V
Integrated system performance V&V
Continuous prototyping and mock-up development

FIG. 25.1
Outline of the human center design process, describing different stages of the design. The use of VR should start already in the analysis phase and continue through the whole design process.

cover the following professions: design engineers, system engineers, operations staff, and human factors staff. Composing the design team, one should have in mind the availability of all team members through the whole design process.

VR is a powerful tool for visualization, and a benefit from using this technique is that good use of VR will allow the multidiscipline design team to communicate and assess design ideas more effectively. All members of the design team possess different expertise and tend to follow different perspectives in order to identify an optimal solution.

The real experts on how to operate the plant are the operators that will have their daily work in the control room. The importance of good communication between the operators and the other members of the design team cannot be overestimated. For refurbishment of existing systems it is recommended that existing operators should be taken into the design team, while for new systems, both experienced and future users should participate.

The operators are not trained to express their design solutions with traditional CAD tools. Using VR tools enables operators to be part of the design process by more simple means. Good VR support software allow the operator to design a control room by clicking and dragging 3D objects, such as instrument panels, large screens, monitors, work place furniture, and other control room equipment. This way the cross-disciplinary team can work on a common reference to the design, which facilitates the experienced end users' contribution to early fault detection and recovery.

The design process begins with a basic concept or idea, for example, a design philosophy. The design philosophy should address all functions of the control room, that is, all activity that is expected to take place within this environment, such as the roles of the operators, staffing size and responsibilities, control room functions, control room layout, instrumentation and control (I&C), and HSI process control needs. Experience from existing control rooms is expected to form the basis of the philosophy.

The analysis phase involves analysis of the control room functional and performance requirements culminating in a preliminary functional allocation and job design. This step usually requires analysis of the assignment of control functions to personnel (e.g., manual control), system (e.g., automatic control), operator support systems, or combinations of the above [2,10,11].

On the basis of the documentation developed in the functional analysis, the design team conducts a task analysis. The purpose of this analysis is to identify the detailed components of human tasks and their characteristic measures [1,3,10]. The task analysis helps to define the HSI requirements for accomplishing operator tasks. The analysis forms the basis for a number of decisions regarding whether combinations of anticipated equipment can fulfill the system performance requirements. At this stage of development, the control room exists as a concept and is described as a conceptual layout in the VR model. A set of requirements defined by the preceding analysis also exists.

The preliminary design phase covers the development of the conceptual design, including the drawing of the initial control room layout, furnishing designs, displays, and controls necessary to satisfy the need identified in the preceding analysis phase.

Different approaches have to be taken in the conceptual design depending on the starting point of the design work. Building the control room from scratch gives the opportunity to utilize a full user-centered design strategy.

NEW CONTROL ROOM

Building the conceptual design for a new control room uses the operator as the center of focus for the new design. The purpose of this phase is not detailed design, but ensuring that all necessary equipment can be placed into the control room in a way that satisfies the functional requirements.

Starting with an empty space, the control room can be built around the operator in accordance with the requirements now specified. Figures 25.2 through 25.4 show examples of how the VR model starts out as an empty space and how new components are added from predefined libraries supported by the equipment vendors (Figure 25.5). In this approach, the conceptual design is not done in CAD, but the drawings can be built using VR software and later converted to CAD.

This example describes the development of a conceptual design for a nuclear power plant control room. In the nuclear power plant, there are normally three or four people located in the central control room. This example uses a shift supervisor who has the overall responsibility for all activities related to the control room, a reactor operator responsible for controlling the reactor, and a turbine operator controlling the turbines and generation of electricity.

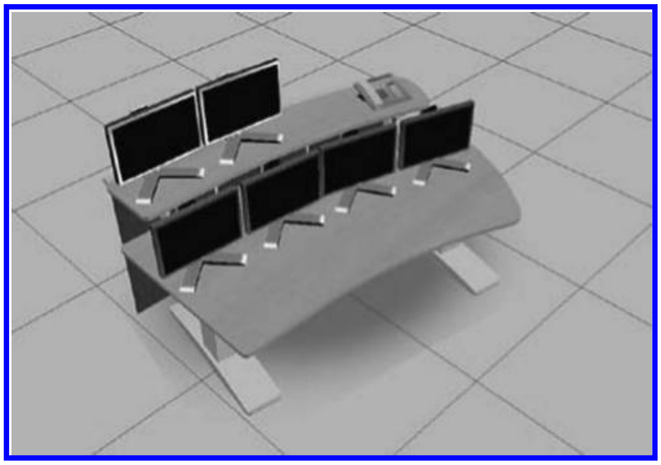

FIG. 25.2
First one operator control station is moved into the design space from the library.

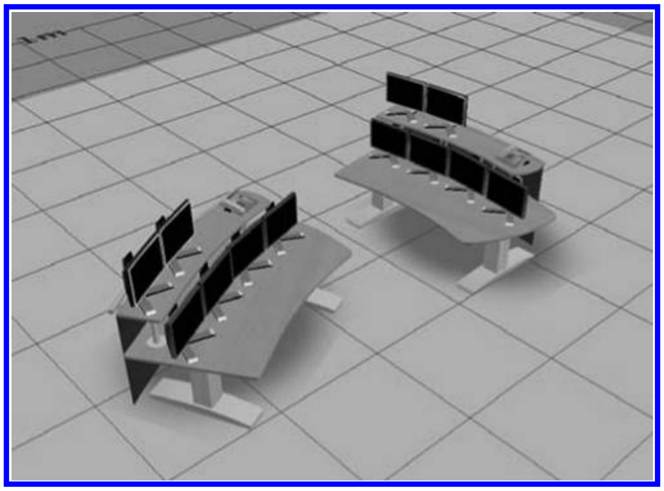

FIG. 25.3
The second operator station is added and rotated to an approximate position.

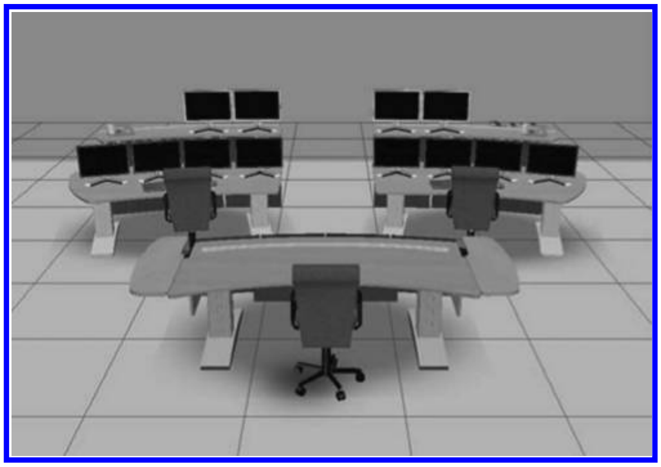

FIG. 25.4
View from the shift supervisor desk, at an early design phase.

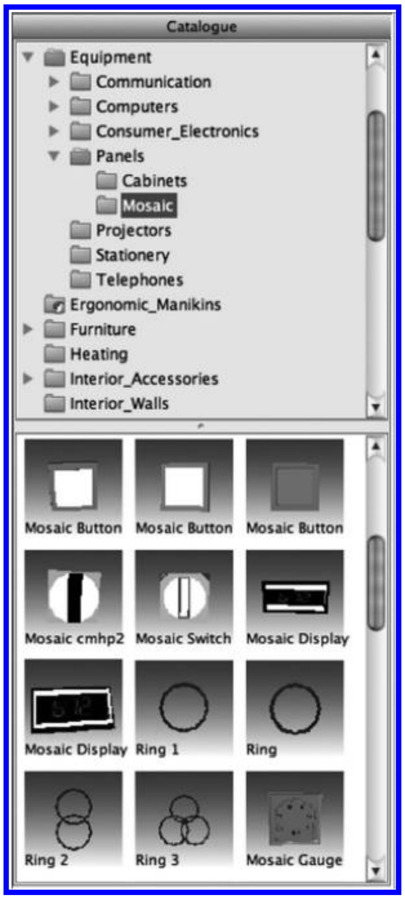

FIG. 25.5
Library of components. A model bank or library of control room components, such as different tables, chairs, VDUs, and control room equipment is an agile tool for starting the design.

After moving the initial three workstations into the model, the sight lines from the shift supervisor workplace (the nearest of the three workstations shown in Figure 25.4) can be visualized and used for guidance in the further location of large screen monitors or control panels. The design team proceeds by adding objects to the control room and arranging them to construct a preferred layout.

Analyses and design team inputs can be considered within the context of operational crew information exchange, in order to support rapid changes in the design.

Refurbished Control Room

In this situation, the physical layout of the existing room is the limiting factor, which has to be taken into consideration. As described above, a number of techniques can be used to convert the control room parts not under revision into a format usable for VR systems. As shown in Figures 25.6 through 25.8, the new equipment is then fitted into the model of the existing control room. If the final V&V requires simulation (integration with a simulator) and interactivity with the model, the designer should consider a full remodeling of the instrumentation kept from the old control room. On the other hand, if simulation is not required, textures from the old control room can be used to represent the instrumentation. In the example shown in Figures 25.6 through 25.8, the walls and stand-up panels are converted from CAD drawings and the instrumentation is represented by photographs of the existing panels.

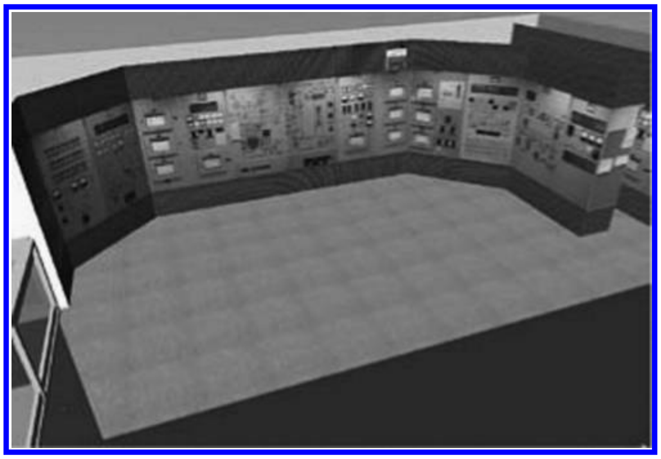

FIG. 25.6
The starting point is an existing control room with fixed equipment intended to be used in the upgraded control room.

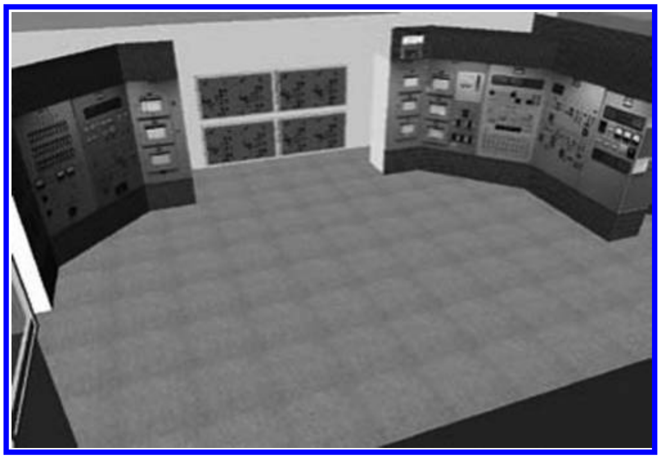

FIG. 25.7
Large screen displays added into the model.

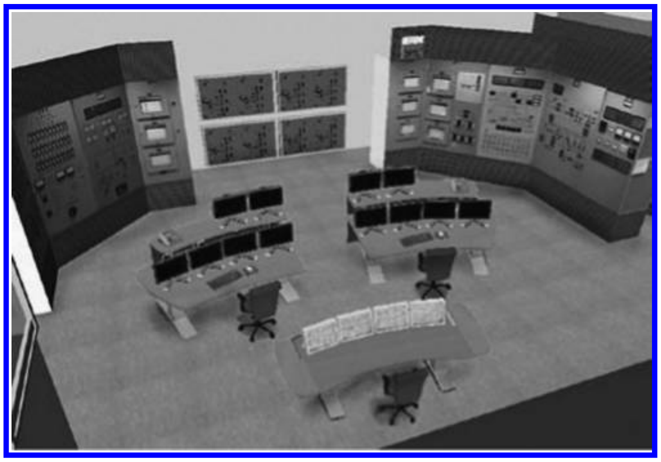

FIG. 25.8
Operator control stations added into the existing control room.

V&V OF THE PRELIMINARY DESIGN

The proposed design should be evaluated on the basis of specifications, and against the applicable functional requirements, design requirements, and design criteria [11]. When a VR model has been developed during the conceptual design phase, this will replace many of the drawings and drafts. The requirements from the analysis can then be evaluated against the VR model.

V&V of the functional design assesses the functions and relationships of personnel and automated equipment in controlling plant processes, and checks the allocation of the task responsibilities of control room operators. The VR model is used instead of physical and paper mock-ups for scenarios with walk-through and talk-through techniques. Figure 25.9 shows an aerial view of a control room conceptual design suitable for V&V at this stage of development. Using a conference room with a good wall projection of the model makes a convenient scene for a team working where whole crews of representative end users can participate in the audit. In the VR model, manikins can represent the crewmembers and indicate their positions stepping through test scenarios.

The functional review is not done on a very detailed process or I&C level; this is left for the detailed design phase. Emphasis should be put on reviewing and verifying that the functional requirements have been accommodated by design ideas and technologies that are feasible, acceptable, and in compliance with all applicable guidelines, standards, and policies. This step should be viewed as a major milestone,

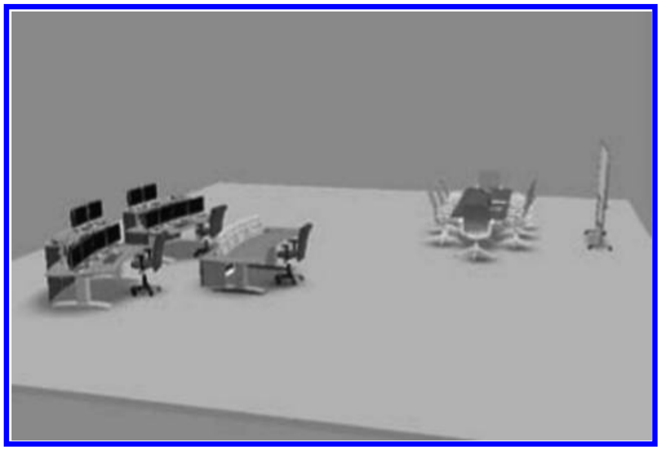

FIG. 25.9
VR model suitable for the conceptual design standards compliance audit.

which enables the subsequent detailed design to proceed with a minimum risk of major functional revisions and changes [1,12].

The detailed design phase results in a detailed design specification necessary for the construction and/or procurement of the control room, its content, operational interfaces, and environmental facilities.

Refinement of the VR model from earlier phases takes place with the aim of producing a final decision on the layout [13]. In this phase, the control panel layout will be specified and designed. If the control room has conventional control panels, the modeling of these panels should be done in VR. If the intention is to use the VR model for the final validation (see simulation and final validation below), modeling should be done with full functionality for instruments intended used in validation scenarios. A good library of components and software support for creating control panel layouts and making connections to a simulator is a necessity for doing this work (Figures 25.10 and 25.11).

The final control room layout can be verified against guidelines using the VR model [2,13,14,16]. Workstation configuration, control room configuration, environment, panel layout, and panel labeling are categories of guidelines suitable for this technique. However, the techniques for utilization of VR technology in guideline verification should be handled with care. Satisfactory verification of guidelines can be achieved only if the VR model and software provides good support for the evaluator, that is, specially developed software tools must be present to help the verification process [17–20]. Tools for measurement of distance and angles like the tools shown in Figures 25.12 and 25.13 are examples of such tools speeding up and making the verification more reliable.

The level of detail in the modeling is deciding whether or not the specific panel layout design, label content, label lettering, and design can be verified using the VR model. Textures are usually not sufficient for this purpose. To be able to judge panel labels, the text size and layout must be correctly modeled in detail or paper specifications should be used in combination with the model.

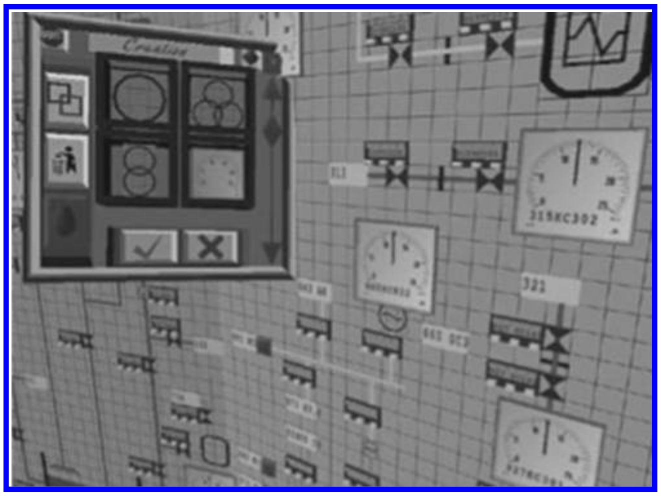

FIG. 25.10
Building control panels using a VR design tool with a library of instruments.

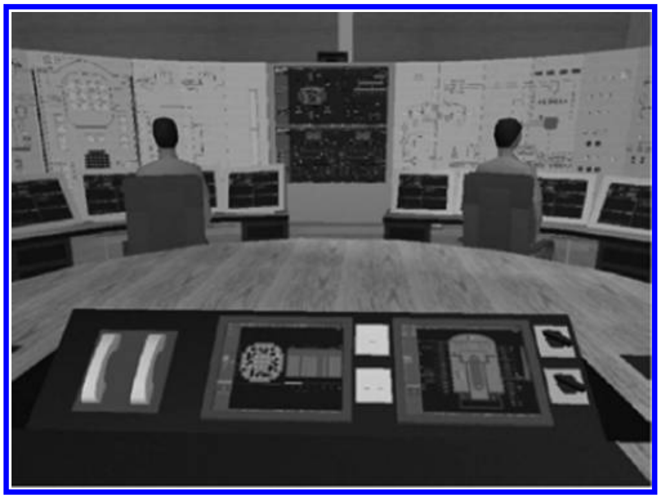

FIG. 25.11
The process of arrangement and layout decisions.

Using specifications from the lighting manufacturers, software can be used to prototype, analyze, and present how a workstation or an object will appear when specific materials and lighting conditions are used in the VR model. Levels of illumination can be read from the calculated illumination model and verified against the guidelines for different work areas in the control room.

The main point of continuous development of the VR model through the whole design process is to detect and correct problems as early as possible. In line with this principle, the guideline verification should not be left out to the last stage. Using the model for verification of guidelines should be an iterative process and take place as early as feasible. Output from the verification should go back into the revised

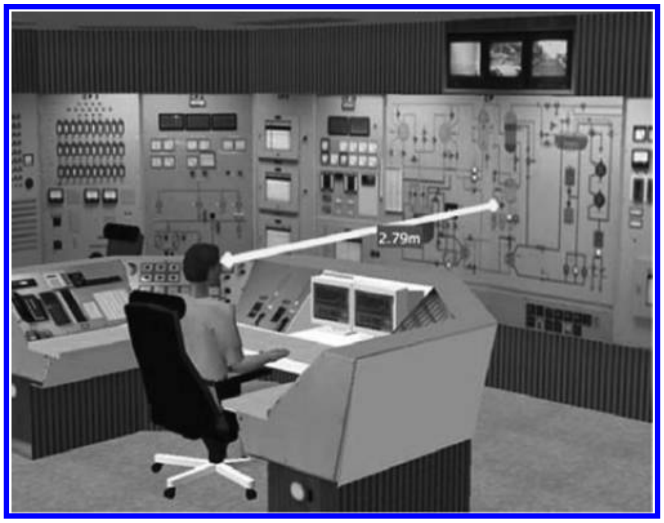

FIG. 25.12
Verification of labeling text size guidelines in a VR model. The length of line drawn from the manikin's head to the control panel (2.79 m) is displayed in the upper right part of the figure.

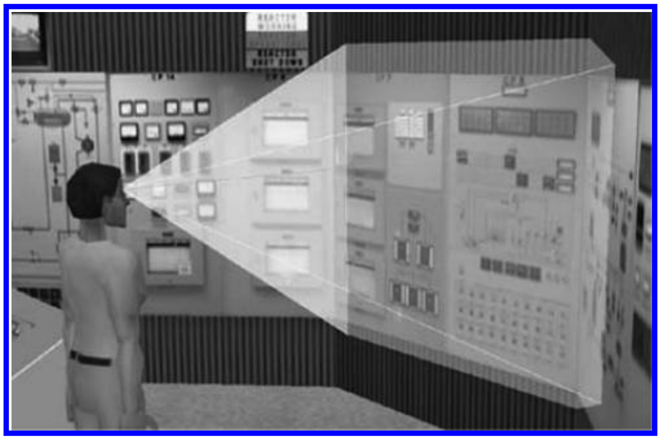

FIG. 25.13
Verification of stand up panel with a tool for displaying the maximum allowed viewing angles.

design specifications. Making the most of the experienced plant operators and human factors staff in the design team is important in this process [1,21].

The final design should be documented in a design description that includes the requirements for verification that the "as built" design is the design resulting from the design process V&V evaluations [2]. In other words, all documents, snapshots, and comments from use of the VR model should be a part of the final design documentation.

Further, the VR model can be used in guideline verification of the final design. If the control room is a refurbished conventional control room, the VR model can also be connected to a simulator and used as replacement of conventional control boards. This way, validation scenarios and training can be run with the control room crew performing their operations in the VR model. However, most industries do not use or require a full-scale simulator of their control rooms and the VR model will therefore, in most cases, only be used for walk-through and talk-through of validation scenarios.

On the other hand, if the control room is a new and fully computerized control room, the gain from using a VR model for full-scale simulation is more limited. If the new control room is built using standard computer equipment, most of the validation can be done from the Video Display Units (VDUs) that will comprise the final system.

CONCLUSION

Current VR technology offers the means for a complete approach for the design of control rooms. Using VR as a tool for testing control room concepts has several advantages. The greatest advantage is perhaps that the technique supports V&V in early phases of the design process, contributing to early fault detection and recovery, thus saving time and money in the later design phases. Although current standards for the design process do not take advantage of this technique, future standards will hopefully integrate and recommend the use of VR in refurbishment and conceptual design of new control rooms.

References

1. ISO 11064-1:2000, *Ergonomic Design of Control Centres—Part 1: Principles for the Design of Control Centers* (ISO 11064-1:2000), 2000.
2. NUREG-0711, *Human Factors Engineering Program Review Model (NUREG-0711, Rev. 2)*, US Nuclear Regulatory Commission Office of Nuclear Regulatory Research, Washington, DC, 2004.
3. IEC 60964, *Nuclear Power Plants—Control Rooms—Design (International Standard 60964 Edition 2.0 2009-02)*. International Electrotechnical Commission, Geneva, Switzerland, 2009.
4. Hill, D., Krause, W., and Gunnarsson, T., The application of human factors engineering for a Major Modernization Project in Sweden—Tools, challenges, and lessons learned from practical experience, *Proceedings of 6th International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology (NPIC&HMIT 2009)*, American Nuclear Society, La Grange Park, IL, April 5–9, 2009.
5. Gunnarsson, T. and Farbrot, J.E., The control room upgrade in the Oskarshamn 1 modernization project, *Proceedings of 4th International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology (NPIC&HMIT 2004), American Nuclear Society Meeting*, Columbus, OH, September 19–22, 2004.
6. ISO 14772-1:1997, *Information Technology—Computer Graphics and Image Processing—The Virtual Reality Modeling Language. Part 1: Functional specification and UTF-8 Encoding First Edition (ISO 14772-1:1997)*, CEN Management Centre, Brussels, Belgium, 1997.
7. ISO/IEC 19776, *Information Technology—Computer Graphics, Image Processing and Environmental Data*

Representation—Extensible 3D (X3D) Encodings (ISO 19776:2009), CEN Management Centre, Brussels, Belgium, 2009.

8. Barnes, M. and Finch, E.L. (Eds.), *Digital Asset Schema Release 1.5.0 Specification*, Krohnos group, Portland, OR, 2008.
9. IEC 61772 Ed.2, *Nuclear Power Plants—Control Rooms—Application of Visual Display Units (VDUs) (International Standard 61772, 2009-4)*, International Electrotechnical Commission, Geneva, Switzerland, 2009.
10. Norwegian Petroleum Directorate, *Human Factors Assessment Method (HFAM)*, Norwegian Petroleum Directorate, Norway, 2003.
11. IEC 1771, *Nuclear Power Plants—Main Control Room—Verification and Validation of Design (International Standard 61771, 1995–12)*, International Electrotechnical Commission, Geneva, Switzerland, 1995.
12. ISO 11064-2:2000, *Ergonomic Design of Control Centres—Part 1: Principles for the Arrangement of Control Suites (ISO 11064-2:2000)*, CEN Management Centre, Brussels, Belgium, 2000.
13. ISO 11064-3:1999, *Ergonomic Design of Control Centres—Part 3: Control Room Layout (ISO 11064-3:1999)*, CEN Management Centre, Brussels, Belgium, 1999.
14. NUREG-0700, *Human-System Interface Design Review Guideline (NUREG-0700, Rev. 2)*, US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC, 2002.
15. Stubler, W.F., O'Hara, J.M., Higgins, J.C., and Kramer, J., *Human Systems Interface and Plant Modernization Process: Technical Basis and Human Factors Guidance (NUREG/CR-6637)*, US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC, 2000.
16. ANSI/HFS 100-1988, *American National Standard for Human Factors Engineering of Visual Display Terminal Workstations (ANSI/HFS 100-1998)*, Human Factors Society, Santa Monica, CA, 1988.
17. Drøivoldsmo, A., Nystad, E., and Helgar, S., *Virtual Reality Verification of Workplace Design Guidelines for the Process Plant Control Room (HWR-633)*, OECD Halden Reactor Project, 2001.
18. Drøivoldsmo, A., Helgar, S., Nystad, E., Johnsen, T., Louka, M.N., and Seregi, L., Verification of workplace design guidelines for the control room: Can virtual reality replace the physical mock-up? In K.I. Fostervold and T. Endestad (Eds.), *Proceedings of Nordiska Ergonomisälskapets Årskonferanse*, Stockholm, Sweden, pp. 73–77, 2000.
19. Louka, M.N., Gustavsen, M.A., and Edvardsen, S.T., Using virtual reality to support multi-participant human-centered design processes for control room design, *Proceedings of 5th International Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology*, American Nuclear Society, La Grange Park, IL, 2006.
20. Sebok, A., Louka, M.N., Drøivoldsmo, A., and Helgar, S., Supporting control centre design with virtual reality, *Proceedings of 2003 HFES Europe Chapter Meeting on Human Factors in Design*, Lund, Sweden, October 2003.
21. Louka, M., Holmstrøm, C., and Øwre, F., *Human Factors Engineering and Control Room Design Using a Virtual Reality Based Tool for Design and Testing (IFE/HR/E-98/031)*, OECD Halden Reactor Project, 1998.